Formation of artificial ionospheric ducts

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[1]   It is well known that strong electron heating by a powerful HF-facility can lead to the formation of electron and ion density perturbations that stretch along the magnetic field line. Those density perturbations can serve as ducts for ELF waves, both of natural and artificial origin. This paper presents the first experimental evidence of plasma modifications associated with ion outflows due to HF heating. The experiments were conducted using the HAARP heater during times that the DEMETER satellite flying at an altitude of approximately 670 km was close to the magnetic zenith of HAARP. The DEMETER satellite has provided in situ measurements of the ion temperature and composition. The experimental results are compared with the numerical model of inter-hemispheric artificial ducts, and it is found that they are in qualitative agreement. **Citation:** Milikh, G. M., K. Papadopoulos, H. Shroff, C. L. Chang, T. Wallace, E. V. Mishin, M. Parrot, and J. J. Berthelier (2008), Formation of artificial ionospheric ducts, *Geophys. Res. Lett.*, *35*, L17104, doi:10.1029/2008GL034630.

1.   Introduction

[2]   It is well known that the presence of field aligned density striations plays a critical role in the propagation of whistler waves in the ionosphere [see, e.g., *Streltsov et al.*, 2006]. These density structures serve as ducts for VLF/ELF waves as the density gradient perpendicular to the magnetic field leads to their total internal reflection. Such density structures has often been observed [*Carpenter et al.*, 2002] to extend over distances covering entire magnetic field lines, trapping, channeling and reflecting whistler waves across conjugate regions. In fact, the presence of such ducts is often considered as a pre-requisite to the generation of Artificially Stimulated Emissions (ASE) such as have been extensively studied by using the Siple VLF transmitter [*Helliwell*, 1988], as well as more recently by the HAARP heater [*Inan et al.*, 2004]. In the HAARP case the VLF waves were generated by modulating the auroral electrojet current at VLF frequencies [see, e.g., *Papadopoulos et al.*, 2003, 2005; *Ferraro et al.*, 1989; *Barr and Stubbe*, 1993].

[3]   The possibility for artificially creating such trans-hemispheric ducts was first discussed by *Perrine et al.*

[2006]. In this paper it was shown that long term (> 15 minutes) continuous HF-heating of the F-region by powerful ionospheric heaters such as HAARP generates a strong heat transport in the ionospheric and magnetospheric plasma, which is often called a "thermal wave". This thermal wave propagates along the magnetic field line through the topside ionosphere and magnetosphere, driving ion outflows, displacing the ambient plasma and leading to the formation of density ducts that stretch along the magnetic field line to the conjugate point. We should mention that upward ion flows from the ionosphere such as the ones predicted by the model were detected by satellites [*Shelley et al.*, 1976], as well as by the EISCAT incoherent radar [*Wahlund et al.*, 1992]. They are ascribed to frictional ion heating by perpendicular electric fields in the ionosphere. Within our concept the frictional heating is replaced by artificial heating using the HAARP facility.

[4]   It is the objective of this letter to present the first experimental evidence of plasma modifications associated with ion outflows due to HF heating. The experiments were conducted using the HAARP heater during times that the DEMETER satellite flying at an altitude of approximately 670 km was close to the magnetic zenith of HAARP, defined at the satellite altitude as the center of the magnetic tube intersecting the heated region in the ionosphere. The DEMETER satellite [*Parrot*, 2002] provided in situ measurements of the ion temperature and composition.

[5]   The letter is organized as following: the next section briefly reviews the theoretical/computational model and its predictions. Section 3 describes the results of the joint HAARP/DEMETER heating experiments. The final section compares the experimental results with the model predictions and discusses their relevance.

2.   Global Ionospheric Heating Model

[6]   The theoretical/computational modeling is utilized by SAMI2 code which has been developed at the Naval Research Laboratory [*Huba et al.*, 2000]. The code is an Eulerian grid-based code, which describes the ionosphere made up of 7 ion species. The equations of continuity and momentum are solved for the electrons and each ion species, with the temperature equation solved for the electrons and the species H^+, He^+, and O^+. Electron density is determined on the basis of charge neutrality. The code includes $E \times B$ drift of the field lines (in altitude and longitude), a neutral atmosphere model, horizontal winds, photo-deposition into the ionosphere, ion chemistry models, and ion inertia. The inclusion of ion inertia is critical since allows for the study of sound wave propagation in the plasma. The SAMI2 model is inter-hemispheric and can thus simulate the plasma along entire magnetic dipole field
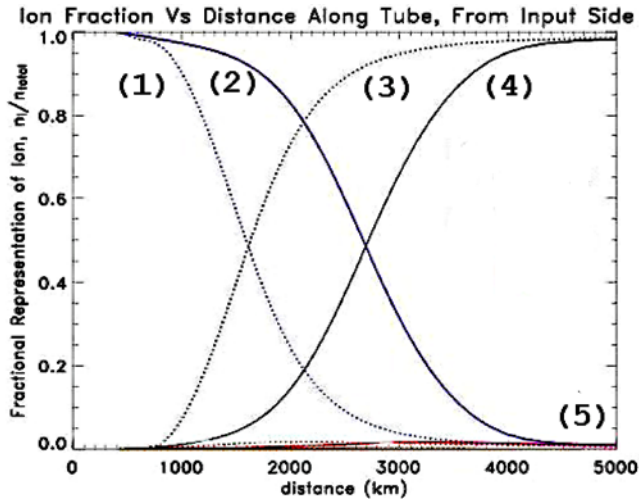
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Figure 1. Predicted changes in ion composition above the heated region during artificial heating. The vertical axis is the fraction of the total ion number density that is a single species, with traces (1) and (2) representing O^+, and traces (3) and (4) representing H^+ under both ambient and heated conditions, respectively. He^+ which is weakly affected by the ionospheric heating, is shown by the trace (5). This plot represents the system after 15 minutes of HF-heating. Heating parameters for this data: $q = 5000$ K/s, $z_0 = 380$ km.

lines. Note that the version of SAMI2 used in this study is limited to mid and low latitudes.

[7] In order to study formation of artificial ducts due to HF-heating SAMI was modified to include a localized flexible source of heating [*Perrine et al.*, 2006]. In addition to Joule heating from electron-ion and electron-neutral collisions and photoelectron heating we include the electron temperature term, representing the HF artificial heating. This term is represented by a Gaussian shaped source given by:

$$Q(K/s) = q \exp\{-(z - z_0)^2/a^2\} \quad (1)$$

$$q = \eta W/V n_e \quad (2)$$

[8] Here Q refers to the total heating rate per electron (in Kelvin per second) delivered to location z. The parameters of this term are the altitude of the heated spot's center z_0, vertical extent of the heated region z, and the heating rate per electron q, which in turn is determined by the radiated HF power W, wave absorption coefficient η, HF-heated volume V, and ambient electron number density n_e. In fact, for current HAARP the heating rate reaches 5,000 K/s.

[9] The height of the heated spot (z_0) is determined by the HF frequency of the heater, and the vertical extent of the region (a) is determined by the plasma frequency of that altitude (ω_e) and the electron cyclotron frequency (Ω_e). It has been shown that strong wave absorption occurs in a relatively thin *region* (10–20 km) between the wave reflection point and the location of the upper hybrid resonance (where $\omega = \sqrt{\omega_e^2 + \Omega_e^2}$). This region is filled with irregularities induced by the HF-heating, that converts the HF
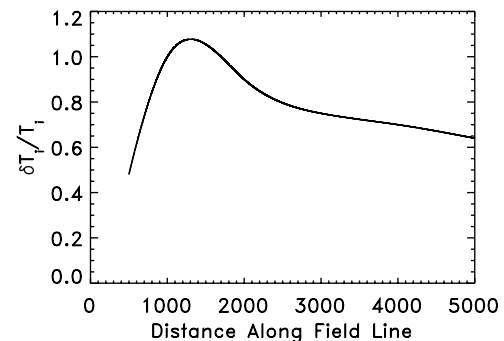
wave to electrostatic wave leading to the so called "*anomalous absorption*" [*Stubbe et al.*, 1994; *Gurevich et al.*, 1996].

[10] A decrease in the electron density which occurs in the heated region [see, e.g., *Duncan et al.*, 1988] leads to the plasma motion along the field line due to ambipolar diffusion. It results in non-uniform motion of the plasma species. Figures 1 and 2 show the variation of ion composition with altitude and of the corresponding ion temperature after 15 minutes of HF-heating obtained from a simulation with the following parameters: q = 5000 K/s, $z_0 = 380$ km. It can be seen that the dominant ion at low altitudes, O^+, rises up quickly during heating to enhance the density at higher altitudes, resulting in a change in the ion composition while the ion temperature almost doubles at a few hundred kilometers above the heated region, following 15 minutes of continuous heating. Since the code is one dimensional the formation of density gradients is implied, but cannot be seen in Figures 1 and 2.

3. Experiments

[11] A number of experimental tests were conducted following the completion of the HAARP heater in 2007. In all of the tests the transmitted power was 3.6 MW, O-mode and the beam was directed along the HAARP magnetic zenith. The modified ionosphere was sensed by two instruments on-board of Demeter, the ICE detector that measures the ionospheric electric field vectors, and the plasma analyzer that measures the ion temperature and composition (O^+, H^+, He^+) [*Berthelier et al.*, 2006a, 2006b]. We report below on cases corresponding to DE-METER-HAARP zenith closest approach less than 300 km. We identified five such cases during our experimental time. However, in two of those cases the F_2-layer critical frequency, f_0F_2, was much lower than the frequency available from the transmitter resulting in very weak absorption and no detectable effects.

[12] Table 1 describes the heater and ionospheric parameters for the remaining three cases. During the transmission and to accommodate a different experiment the transmitter was modulated by ULF frequency. The effect of the modulation was to reduce the effective constant wave power by a factor of approximately two.

Figure 2. Changes in ion temperature above the heated region during artificial heating. Computed at the same conditions as in Figure 1.

Table 1. List of the Heater and Ionospheric Parameters Along With the Closest Approach[a]

Date	Time (UT)	f_0F_2 (MHz)	HF Frequency (MHz)	ERP (MW)	Closest Approach (km)
4/24/07	06:26:30–06:59:30	3.8	3.2	370	55
8/01/07	06:42:00–06:52:00	3.0	2.85	280	94
8/24/07	06:55:00–07:15:00	3.8	3.3	410	137

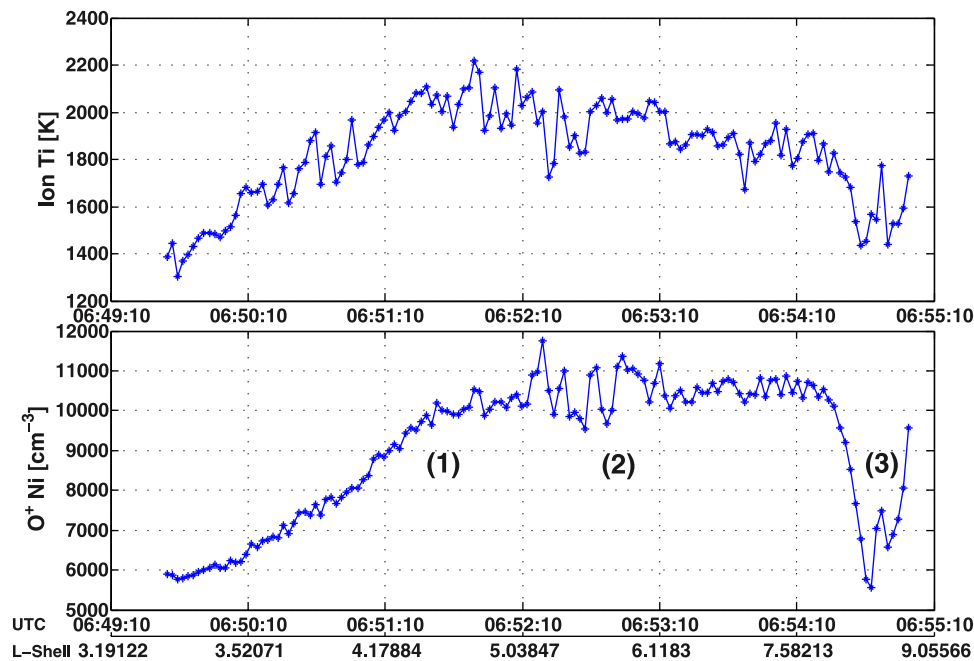[a]Distance of DEMETER to HAARP in the experiments discussed.

[13] In all of the above cases the on-site HAARP diagnostics indicated a smooth F-region layer, negligible D/E region absorption and absence of electrojet current. Figures 3 and 4 show key measurements made during two of the above DEMETER passes, 4/24/07 and 8/01/07. Figure 3 shows ion temperature and density profiles for the first case of Table 1. Both the ion temperature and O^+ density rise due to the HF-heating by about $60-70\%$. The rise of the temperature and density was detected over $3-4$ minutes corresponding to $1,300 - 1,700$ km distances. Reduction in the H^+ density correlated with the heating was also observed (not shown here) near the closest approach. The temperature peak occurs one minute earlier than the density. That corresponds to a lateral shift of approximately 480 km. Notice also a spatial asymmetry of the ion outflows directed towards the incoming satellite (see Figure 3). Notice the presence of a duct associated with the density gradient between 06:51:00 and 06:51:30 (marked by (1) in Figure 3), the presence of a cavity between 06:54:30 and 06:55:00 (marked by (3)), as well as a series of few percent short length ducts between 06:52:00 and 06:53:30 (marked by (2)). The latter correspond to magnetosonic waves at the 0.1 Hz modulation and are correlated with simultaneous detection of 0.1 Hz oscillations in both horizontal components of the electric field in the region of closest approach. They will be examined in a future publication.

[14] Figure 4 corresponds to the second case of Table 1. It shows a sharp peak of T_i ($\delta T_i/T_i^o \simeq 2$), and n_i ($\delta n_i/n_i^o \simeq 2.5$), caused by the ion outflows. These two peaks are shifted by 1 min (480 km). Furthermore starting at 6:47:10 a strong increase of O^+ density occurs along with the increase of H^+ and He^+. The magnetometer data reveal a sharp peak at this time. We attribute this to the occurrence of natural ion precipitation. In fact, data obtained from the DMSP F16 satellite indicate the presence of strong precipitation at latitude of $66°$ and higher where Demeter moved at this time. Therefore the increase in O^+ density due to HF-heating was masked by the precipitation.

[15] Third case of Table 1 is similar to the second one (the figure is not presented). We detected increase in T_i and O^+ density due to HF-heating ($\delta T_i/T_i^o \simeq 0.3$, $\delta n_i/n_i^o \simeq 1.0$). Reduction of the H^+ and He^+ was also observed. Similarly to the second case the natural ion precipitation occurred at the late stage of these observations as revealed by the DMSP F16 satellite, which led to the ion density perturbations.

4. Discussion

[16] We presented the first experimental verification of strong ion outflows and formation of the ionospheric ducts by F-region ionospheric heating. Their generation requires

Figure 3. The ion temperature and O^+ density measured by Demeter at 670 km during artificial heating 04/24/07. The x-axes show the time of the observations, along with the corresponding satellite latitude, longitude and L-shell. HAARP is located at L = 4.95.
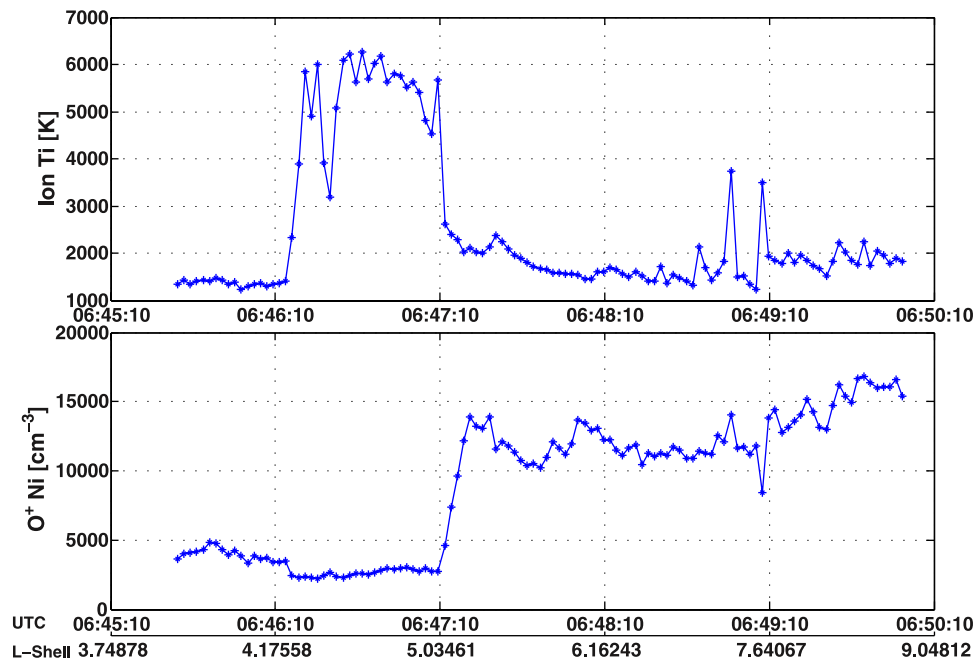
Figure 4. The same as in Figure 3 but measured on 08/01/07.

strong F-region heating which is known to be optimal in a quiet ionosphere with a distinct smooth F_2 region, and minimal D/E region absorption. The ion outflows and density structures are best detected by satellites passing within a few hundred kilometers to the HAARP magnetic field line.

[17] In the frequency range of $3-6$ MHz the HF-heated region at $250-270$ km is elliptical with the short axis $60-80$ km and long axis $80-100$ km. The abovementioned spread of the ion outflows by $1,300-1,700$ km is partly due to $E \times B$ drifts. In fact, the electric field component perpendicular to the DEMETER orbit is $25-30$ mV/m, corresponding to drift velocity directed along the DEME-TER orbit in the range $0.4-0.5$ km/s. Since the HF-heating by HAARP starts $10-15$ minutes prior to the DEMETER over-fly the ion outflows spread by about 500 km, which is less than that observed, although some other phenomenon like winds could play a role.

[18] Furthermore the electric field component perpendicular to the DEMETER orbit is in E-W direction, resulting in southward ion drift, i.e. toward the satellite. It accounts for the presence of the spatial asymmetry toward the incoming satellite in Figure 3b.

[19] We should finally comment on the observed shift between the peaks of the perturbed ion temperature and the density of the oxygen ions (see Figure 3). We attribute this to the fact that two different transport mechanisms are involved, as seen in our model. First, the thermal wave caused by the electron heating transfer energy excess to ions. Later on the heating perturbs the electron density at the heating spot. This creates a temporary pressure imbalance which drives the density perturbations along the field line leading to ion outflows.

[20] Our computations reveal that at the heating rate such as produced by HAARP the expected ion temperature increase is approximately 70% at a distance 400 km above the heated spot along the field line, while the O^+ density rises by about 20%. This is in qualitative agreement with the observations. Notice, however, that the version of SAMI2 used here was appropriate to low and mid latitudes. A version of the code which describes high latitudes has been developed at NRL and we are planning to use it in quantitative comparisons with experiments.

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